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1 TECHNICAL PAPER

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Evaluation of CO₂ emissions from railway resurfacing maintenance activities

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Abstract

This paper is the world first to investigate the CO₂ impact of railway resurfacing in ballasted track bed maintenance. Railway resurfacing is an important routine maintenance activity that restores track geometry to ensure safety, reliability and utility of the asset. This study consisted of an extensive field data collection from resurfacing machineries (diesel-engine tamping machines, ballast regulators and ballast stabilisers) including travel distances, working distances, fuel consumption and construction methodologies. Fuel consumption was converted to a kg CO₂/m using the embodied energies of diesel. Analyses showed that tamping machines emitted the highest CO₂ emissions of the resurfacing machineries, followed by ballast regulators and ballast stabilisers respectively. Tamping machines processed 4.25 metres of track per litre of diesel, ballast regulators processed 6.51 metres of track per litre of diesel and ballast stabilisers processed 10.61 metres of track per litre of diesel. The results were then compared to previous studies and a parametric study was carried out to consider long-term resurfacing CO₂ emissions on Australian railway track. The outcome of this study is unprecedented and it enables track engineers and construction managers to critically plan strategic rail maintenance and to develop environmental-friendly policies for track geometry and alignment restoration.

Keywords: Carbon footprint, Green house gas emission, Railway resurfacing, Strategic maintenance, Construction management.

1 Introduction

There has been a steady increase in the reliance on fossil fuel derived energy for the last century, which has resulted in increased CO₂ emissions (Lombard et al., 2008; US EPA, 2014; Raupach et al., 2007). Transportation has been fundamentally embedded in all activities in a society, ranging from logistics of medicine, raw materials, consumable products, technology products, energy sources, and other wide ranges of related human activities. The transportation sector is thus a significant contributor to CO₂ emissions (Lenzen, 1999; Ortmeyer and Pillay, 2001), mainly due to increasing infrastructure development and global transport requirements. It also contributes to air pollution through air borne particle emissions from stationary and mobile sources (Colville et al., 2001). It is important to note that substantial railway transportation growth is expected in the near future (McGregor, 2013), and all modes of transportation sectors have an obligation to reduce CO₂ emissions from all phases of their life cycles, including construction, maintenance, operations and end of life (Kaewunruen et al., 2014; 2016).

Routine railway maintenance is required to ensure the safety, reliability, functionality and utility of the railway assets. Ballasted track bed maintenance activities consist of renewal and reconstruction tasks, ballast cleaning, resurfacing, rail-head grinding and re-railing. All of these activities are generally performed with the assistance of diesel power machineries. Railway track bed resurfacing restores track geometry and alignment to an acceptable condition (Railcorp, 2013). Machines for a resurfacing task consist of tamping machines (diesel engine), ballast regulators, and dynamic stabilisers. Tamping machines are used for packing, lifting and lining the track bed. Ballast regulators replenish ballast and rebuild shoulder profiles; then ballast stabilisers pass through the track in order to consolidate the ballast aggregates to a uniform fit ensuring a good interlocking between the crushed aggregates. The advantages of resurfacing include increased safety, extended track life, reduced riding discomfort, improved train-track interaction, and functionality of the infrastructure.

114 A critical literature review regarding CO₂ emissions from railway maintenance shows a very
115 limited and lacking detail of actual activity-based measurement and estimation, and in fact the use
116 of broad assumptions makes it difficult to verify the results. Milford and Allwood (2010)
117 investigated the impact of rail designs over the life cycle. Due to limitation of data and previously
118 published literature, they made assumptions regarding the fuel consumptions and track-processing
119 rates of railway resurfacing machineries. They rightly recommended that further research be carried
120 into the fuel consumption and CO₂ emissions from the machineries to verify the accuracy of their
121 study. In addition, Kiani et al. (2008) investigated a life-cycle assessment of railway track beds,
122 including ballasted and ballastless tracks. The authors found that over the life of the infrastructure,
123 slab track bed constructions were not associated with higher CO₂ emissions than ballasted track
124 bed. The maintenance CO₂ emissions study were based on a large number of assumptions and
125 variable industry experiences; however, no field data collection was carried out to verify the
126 accuracy. Therefore, this study herein expands these research horizons and removes unclear
127 assumptions by carrying out extensive site-based data collection and cost-based reviews on
128 resurfacing machineries and numerous interviews with relevant project managers and engineers in
129 NSW, Australia.

130 The goal of this study is to estimate more accurately the CO₂ emissions from railway
131 resurfacing practices. Field data collection and evidence-based review of project costs was carried
132 out to ascertain the resurfacing methodology, travel distances, working distances and the fuel
133 consumptions of diesel powered machineries (tamping machines, ballast regulators and ballast
134 stabilisers). The study included Australian track bed construction methodologies, emissions factors
135 and existing machineries used in ballasted track bed resurfacing. This paper aims at reporting
136 CO₂/m metric in order to develop simplified calculations for parametric study.

137 A parametric study is carried out to forecast the future CO₂ emissions from railway
138 resurfacing activities. The parametric study has utilised the data collected, design life expectation
139 and standard track maintenance planning. The model considers 20, 50 and 100-year life-cycles of

140 ballasted track bed. The exclusions from this data record include the machinery manufacture
141 emissions (due to difficulty in obtaining accurate data from the manufacturers), the fuel
142 consumption of work crews travelling to the depot or stabled locations (difficulty in accurately
143 estimating the distances due to varied stabled locations), the fuel tanker used to re-fuel the
144 resurfacing machineries (difficulty in accurately estimating distances due to varied stabled and re-
145 fuelling locations) and hand tamping tools (as the results are negligible compared to the large
146 resurfacing machineries). Note that there have recently been new types of tamping machines, which
147 are more efficient and adopt electric power and hybrid (e.g. Plasser and Theurer's new models).
148 However, these new types of tamping machines are not common in global practice at this stage and
149 its use is still limited (e.g. in Europe and, to an extent, some rail construction companies). In this
150 study, the scope of field measurements is placed on diesel-engine tamping machines. The study into
151 the performance of hybrid and electric powered engine tamping machine will form a future study.

152 The outcome of the study will however be provided to decision makers and project planners
153 (e.g. master schedulers, construction manager, maintenance and assets engineers) with a reasonably
154 accurate CO₂ emissions estimates that can be used to plan and forecast CO₂ emissions from
155 resurfacing activity when selecting materials for track beds. Researchers focusing on new railway
156 infrastructure will benefit from this investigation by having reasonably accurate estimates when
157 planning life-cycle assessments for ballasted railway constructions.

158

159 **2 Methodology**

160 Railway resurfacing activity is used to restore track geometry, restore ballast shoulder
161 widths and replenish ballast crib levels (in order to improve lateral resistance of railway track).
162 Resurfacing practices take place to restore railway track bed after re-construction activities and as a
163 periodic maintenance activity. '*Re-construction resurfacing*' occurs where sections of track
164 including the track bed are replaced and work needs to be carried out to ensure the track bed is
165 returned to an acceptable condition. The re-construction resurfacing can experience extended delays

166 as several passes (machines proceeding in working mode is considered a pass) over the same
167 location may be required. '*Periodic maintenance activities*' occur routinely to ensure the ballasted
168 track bed remains or is returned to an acceptable condition. Two forms of targeted periodic
169 maintenance activities are performed: cyclic resurfacing and resurfacing for defects removal. Cyclic
170 resurfacing is a periodic activity (either determined by age or traffic) in which track geometry is
171 restored as an acceptable condition (preventative measure). Corrective resurfacing for defects
172 removal occurs in problematic areas where defects in top or line geometry require corrections
173 (Sydney Trains, 2013).

174 For future research, using game theory to identify carbon-efficiency decision process,
175 understanding the project planning and scheduling is essential. The planning methodology of
176 railway resurfacing projects is: civil maintenance crews and track inspection vehicles are used to
177 identify defects. Due to the complexity and weekday use of the NSW rail network, weekend
178 shutdowns (possessions) are the ideal time to carry out resurfacing works (Sydney Trains, 2013).
179 The task scheduling is generally carried out by the resurfacing department. The first step in the
180 construction planning is to ascertain which machineries are available for the possession weekend
181 and do not overlap with other construction projects that require resurfacing support over the
182 same period. Consultation is carried out with the network or asset owners to identify known
183 geometric defect areas; with previous program sheets identifying the location of recurring
184 defects. The allocation of plant is prioritised to recurring defect areas with the remaining time set
185 for cyclic resurfacing (Sydney Trains, 2013).

186

187 **2.1 Railway resurfacing machinery data collection**

188 The data collection commenced with re-fuelling the resurfacing machineries to the capacity
189 of the fuel tanks. Then a measurement is taken for the travel distance. Once at the worksite, the
190 distance of track processed in work mode is recorded and the number of passes of each of the
191 machineries is recorded. The number of passes varies depending on the project. Re-constructions

will typically require the tamping machine and ballast regulator to process the track multiple times to ensure the correct track height is achieved. However, production tamping typically requires only a single pass as the lifting height is small and can be achieved with one pass. The distance travelled to return to the stabling location is recorded; with this process repeated until the resurfacing works are complete. Finally, the machineries are refuelled by a mobile fuel tanker and the fuel consumption recorded. The machineries observed in the data collection are shown in Table 1.

2.2 Estimating CO₂ emissions from railway resurfacing machineries

Diesel powered resurfacing machineries are used to reduce manual labour and to increase the distance of track bed to be resurfaced. The reduction in manual labour introduces diesel powered machineries which contribute significant CO₂ emissions.

The CO₂ emissions from the machineries used in railway re-construction projects were evaluated by using the National Greenhouse Gas and Reporting Scheme (Department for Climate Change and Energy Efficiency, 2013) technical guidelines database and the Australian National Greenhouse Accounts Factors (NGA, 2012). The NGA (2012) determined that the emissions from a given fuel be estimated using Equation 1.

$$E_{ij} = Q_i EC_i EF_{ij} \quad (1)$$

where:

E_{ij} (kg) is the emissions of gas type j for fuel type i ;

Q_i (kg) is the quantity of type i fuel consumption;

EC_i (GJ/kL) is the energy content factor of type i fuel;

EF_{ij} (kg/GJ) is the gas j emission factor for fuel i .

Since CO₂ is the largest contributor to greenhouse gas (GHG) emissions (Carbon Neutral, 2011), only this gas type has been considered in the current study. The fuel used by the machines for the trackwork investigated in the current study was diesel. The EC_{diesel} value is 38.6 GJ/kL

217 according to NPA (2012 pp 15), and the $EF_{\text{diesel-CO}_2}$ value is 69.2 kg CO₂/GJ (Department for
 218 Climate Change and Energy Efficiency, 2012), where kg CO₂/GJ stands for kilogram of CO₂
 219 emission per gigajoule of energy. Hence for estimating CO₂ emission by diesel fuel, Eq. (1) can be
 220 written as

$$E_{\text{diesel-CO}_2} = Q_{\text{diesel}} EC_{\text{diesel}} EF_{\text{diesel-CO}_2} \quad (2)$$

$$= 2671.1 Q_{\text{diesel}}$$

222

223 **3 Results and Discussion**

224 The results of the data collection, including travel distances, work distances, fuel
 225 consumption and resurfacing activity, are shown in Table 2. The total fuel consumptions for
 226 grouped machineries (grouped as tamping machines, ballast regulators and ballast stabilisers); travel
 227 distances, working distances and fuel consumption over metre of track processed for each
 228 machinery type are shown in Table 3.

229 Table 4 shows the estimated CO₂ emissions from the railway resurfacing machineries
 230 from the site data collection. The results of study show that on average the tamping machines are
 231 able to process 4.25 metres of track for every litre of fuel used, processing 9,683 metres of track
 232 using 2,279 litres of diesel; the ballast regulators processed 6.51 metres of track for every litre of
 233 fuel used, processing 9,301 metres of track with 1,429 litres of diesel; whilst the ballast
 234 stabilisers processed 10.61 metres of track for every litre of fuel used, processing 6,940 metres of
 235 track with 654 litres of diesel consumed.

236 The estimated CO₂ emissions from the railway resurfacing activities in the data collected
 237 showed that tamping machines generated 6,088 kg CO₂ over 9,683 metres of track processed,
 238 ballast regulators generated 3817 kg CO₂ over 9,301 metres of track processed and ballast
 239 stabilisers generated 1747 kg CO₂ over 6,940 metres of track processed. The results show that
 240 the tamping machines emitted 37 % more CO₂ emissions than the ballast regulators and 71 %

241 more CO₂ emissions than the ballast stabilisers. The ballast regulators emitted 44 % more CO₂
242 emissions than the ballast stabilisers.

243 The results of the data collection were then compared over a 1,000 km track processed
244 distance. As shown in Table 5, to process 1,000 km of ballasted railway track, the tamping
245 machines consumed 235,360 litres of diesel fuel and generated 628,675 kg CO₂. To process 1000
246 km of ballasted railway track, the ballast regulators consumed 155,360 litres of diesel fuel and
247 generated 414,985 kg CO₂. To process 1000 km of ballasted railway track, the ballast stabiliser
248 consumed 94,240 litres of diesel fuel and generated 251,727 kg CO₂. In total, the estimated CO₂
249 emissions from all resurfacing machineries emitted 1,295,387 kg CO₂ for resurfacing 1000 km of
250 ballasted track bed.

251 Research shows that machineries stabled closer to the worksite location save time and
252 delay. This is done to maximise the time to perform resurfacing activities during shutdowns and
253 reduce the likelihood of being delayed.

254

255 **4 Comparative Study**

256 The results were compared with previous studies carried out by Kiani et al. (2008) and
257 Milford and Allwood (2010). Table 6 shows the assumptions made by these studies. Table 7
258 shows the comparison of diesel fuel consumption for resurfacing 1,000 km of ballasted railway
259 track between the current study, Kiani et al. (2008) and Milford and Allwood (2010). Kiani et al.
260 (2008) and Milford and Allwood (2010) used a slightly different methodology, with Kiani et al.
261 (2008) reporting on CO₂ emissions from a tamping machine and ballast regulator whilst Milford
262 and Allwood (2010) reported on tamping machines and stoneblowing machines.

263 Kiani et al. (2008) used fuel consumption per hour (litre/hour) and construction speed
264 (hours/km) to ascertain the total fuel consumption per kilometre. The values used by Kiani et al.
265 (2008) for fuel consumption in tamping machines were 15 litre/hour with a construction speed of
266 32 hours/km. The ballast regulator values were 10 litre/hour with a construction speed of 17

267 hours/km. The authors found that tamping machines used 480,000 litres of diesel for every 1000
268 kilometres (km) of track processed, with the ballast regulator consuming 170,000 litres for every
269 1000 km of track processed. The total diesel fuel consumption for resurfacing machineries in the
270 Kiani et al. (2008) study was 650,000 litres.

271 Due to limited literature, Milford and Allwood (2010) assumed fuel consumption and
272 working distances, which were based on new machineries. Milford and Allwood (2010) used a
273 fuel consumption of 70 litre/hour and a construction distance of 1200 m/hour for tamping
274 activities. Milford and Allwood (2010) used stoneblowing machines (slightly different
275 construction methodology when compared to this study); with the stoneblowing consuming 70
276 litre/hour with a construction distance of 440 m/hour. The results showed that tamping consumed
277 58,380 litre of diesel per 1000km and stoneblowing used 159,380 litres of diesel per 1,000 km.
278 The total diesel fuel consumption in the study was 217,470 litres.

279 The results of the Kiani et al. (2008) study were compared to this study. Kiani et al.
280 (2008) estimated 40% more fuel consumption for combined tamping and ballast regulating
281 activities. When the results of all resurfacing (tamping machines, ballast regulating and ballast
282 stabilising) from this study are compared to Kiani et al. (2008); Kiani et al. (2008) estimated
283 25% more diesel fuel consumption. The results Kiani et al. (2008) predicted show higher CO₂
284 emissions compared to this paper, as the authors based the data on personal communications. As
285 witnessed in the data collection in this study, delays during working are common, which may not
286 have been taken into account in the estimate of Kiani et al. (2008).

287 Comparing Milford and Allwood (2010) to the tamping machine results of this study; this
288 study estimated three times more fuel consumption in tamping machine activities. Milford and
289 Allwood (2010) estimated a total of 217,470 litres of diesel fuel consumption for tamping and
290 stoneblowing a 1000 km section of railway track (this is a different construction methodology to
291 the one used in this study). When comparing the total resurfacing fuel consumption between
292 Milford and Allwood (2010) to this study; this study estimated 55% more diesel fuel

293 consumption for resurfacing. The results are significantly higher than those estimated by Milford
294 and Allwood (2010). However, due to limited information, Milford and Allwood (2010) based
295 their results on the internet sources and personal communications, which most likely did not
296 account for delays, which are commonly experienced in practice.

297 Table 8 shows the comparisons in CO₂ emissions for resurfacing of 1,000 km of ballasted
298 railway track between the abovementioned study, Kiani et al. (2008) and Milford and Allwood
299 (2010). Kiani et al. (2008) estimated 1,282,138 kg CO₂ from tamping a 1000km of railway track,
300 51 % more than the findings in this study. When comparing total resurfacing CO₂ emissions,
301 Kiani et al. (2008) estimated 1,736,229 kg CO₂ per 1000km of railway track, which is 26% more
302 CO₂ emissions when compared to the estimates of this study. Kiani et al. (2008) estimated higher
303 CO₂ emissions for tamping machines and total resurfacing compared to this study, likely due to
304 the fact that the machine data used in the Kiani et al. (2008) study was the preferable scenario
305 which did not include delays as were experienced in the field study. There is also a difference in
306 country specific diesel fuel emissions factors used; as the Australian emissions factor is slightly
307 higher than that of the UK fuel data.

308 Milford and Allwood (2010) found that tamping 1,000 km of ballasted railway track
309 emitted 155,540 kg CO₂; three times less CO₂ emissions when compared to tamping CO₂
310 emissions estimates from this paper. When comparing total resurfacing CO₂ emissions, Milford
311 and Allwood (2010) estimated 580,488 kg CO₂ for 1,000 km of railway track, which is 55% less
312 than the CO₂ emissions than estimated in this paper. Milford and Allwood (2010) estimated
313 lower CO₂ emissions for tamping machines and total resurfacing compared to this study, likely
314 due to the fact that the machine data used in the Milford and Allwood (2010) used machine
315 manufacturers specifications and speeds and these sources do not include incidents or delays that
316 may occur in practice. There is also a difference in country specific diesel fuel emissions factors
317 used. Australian emissions factors are slightly higher than that of the UK.

318 When comparing the CO₂ emissions from tamping machines between Kiani et al (2008)
319 and Milford and Allwood (2010); Kiani et al. (2008) estimated 10 times more CO₂ emissions
320 from tamping machine practices. When comparing the total resurfacing activities of Kiani et al.
321 (2008) to Milford and Allwood (2010); Kiani et al. (2008) estimated three times more CO₂
322 emissions. The estimates from Kiani et al. (2008) are significantly higher than that of Milford
323 and Allwood (2010); this is due to Kiani et al (2008) using a much lower construction speed (32
324 hours/km) whereas Milford and Allwood (2010) used a much larger construction speed (50
325 minutes/km).

326 The purpose of this investigation was to report on the CO₂ emissions from railway
327 resurfacing practices and this was achieved by carrying out an extensive field-based study of
328 railway resurfacing practices. The need for this study comes from broad assumptions made by
329 previous authors reporting on maintenance CO₂ emissions in life-cycle analyses. The findings of
330 this study show that the estimates found in the previous studies were either higher or lower than
331 the results found in this study. The assumptions used in previous studies were verifiable and this
332 study highlights the discrepancies in data and the potential risk of using various CO₂ emission
333 models. The outcome of this paper is aimed at providing an alternative source of more accurate
334 CO₂ emission database obtained from extensive and detailed field studies.

335

336 **5 Parametric Study**

337 A parametric study has been carried out to estimate the CO₂ emissions for various
338 resurfacing distances and time periods. Currently in Australia, there is an estimate of over 42,000
339 kilometres of railway tracks (Australasian Railway Association, 2014). For the purpose of the
340 parametric study, the scale variables of 1,000, 2,000, 5,000 and 10,000 kilometres of ballasted
341 track bed resurfacing have been considered for the annual renewals. The variations in annual
342 resurfacing distances allow decision makers and planners to analyse the impact of railway
343 resurfacing on maintenance CO₂ emissions when different scenarios are considered.

344 Figure 1 shows the CO₂ emissions from resurfacing activities. If 1000km of ballasted
345 track was resurfaced annually 1,290,750 kg CO₂ would be emitted. After 20 years of resurfacing
346 1000km annually 25,815,000 kg CO₂ would be emitted. After 50 years of resurfacing 1000km
347 annually 64,537,500 kg CO₂ would be emitted.

348 If 2000km of ballasted railway track was resurfaced annually 2,581,500 kg CO₂ would be
349 emitted. After 20 years of resurfacing 2000km annually 51,630,000 kg CO₂ would be emitted.
350 After 50 years of resurfacing 2000km annually 129,075,000 kg CO₂ would be emitted.

351 If 5000km of ballasted track was resurfaced annually 6,453,750 kg CO₂ would be
352 emitted. After 20 years of resurfacing 5000km annually 129,075,000 kg CO₂ would be emitted.
353 After 50 years of resurfacing 5000km annually 322,687,500 kg CO₂ would be emitted.

354 If 10,000km of ballasted track was resurfaced annually 12,075,500 kg CO₂ would be
355 emitted. After 20 years of resurfacing 10,000km annually 258,150,000 kg CO₂ would be emitted.
356 After 50 years of resurfacing 10,000km annually 645,375,000 kg CO₂ would be emitted.

357 Based on these results, it is found that ballasted track bed resurfacing practices emit a
358 significant amount of CO₂ emissions. As a case study, the parametric study can provide a
359 reasonably accurate set of estimates of CO₂ emissions from resurfacing practices considering
360 various track distances over different stages of a life-cycle, which can be used by planners and
361 decision makers as a CO₂ emissions forecasting tool.

362

363 **6 Conclusion**

364 This paper estimates the CO₂ emissions from railway resurfacing activities by carrying
365 out an extensive field study, which observed the travel distances, working distances and fuel
366 consumptions of tamping machines, ballast regulators and ballast stabilisers. The field-based
367 study provided accurate data from resurfacing machineries. The fuel consumptions were
368 converted to CO₂ emissions and compared to previous studies. The results will be used in future

369 life-cycle analyses and for reporting on emissions for maintenance operations. The outcome will
370 establish a decision-making framework to enable carbon-efficient practice in railway industry.

371 According to the field data and extensive review of project costs, it is found that tamping
372 machines processed 4.25 metres of track bed per litre of diesel fuel; ballast regulators processed
373 6.51 metres of track bed per litre of diesel fuel and ballast stabilisers processed 10.61 metres of
374 track bed per litre of diesel fuel. The results of previous studies by Kiani et al. (2008) and
375 Milford and Allwood (2010) showed that there was a vast difference in fuel consumption and
376 subsequent CO₂ emissions, with Kiani et al. (2008) estimating 10 times more CO₂ emissions
377 than Milford and Allwood (2010). These estimates could not be verified but the difference was
378 due to assumed construction speed.

379 The results of the field data collection compared to the previous studies showed that
380 Kiani et al. (2008) estimated 26% more CO₂ emissions; whilst Milford and Allwood (2010)
381 estimated 55% less CO₂ emissions. As stated, the difference in results was due to construction
382 speeds, for instance, not taking into account real-time delays experienced in practice and also a
383 difference in country specific diesel fuel emissions factors between the UK and Australia.

384 A parametric study considered resurfacing activities for various lengths of track over
385 different stages of the railway infrastructures life-cycle. The results found that resurfacing 1,000
386 km of resurfacing contributed 25,907,740 kg CO₂ after 20 years and 64,769,350 kg CO₂ after 50
387 years. 2,000 km of resurfacing contributed 51,815,480 kg CO₂ after 20 years and 129,538,700 kg
388 CO₂ after 50 years. 5,000 km of resurfacing contributed 129,538,700 kg CO₂ after 20 years and
389 323,846,750 kg CO₂ after 50 years. 10,000 km of resurfacing contributed 259,077,400 kg CO₂
390 after 20 years and 647,693,500 kg CO₂ after 50 years.

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Table 1. List of machineries covered in the data collection.

Machine	ID	Characteristics	Model	Engine Capacity
Tamper	1	Switch / points tamper	Plasser - 07/275	9.05 Litres
Tamper (2)	2	Mainline	Plasser - 09-16 Cat	6.99 Litres
Tamper (3)	3	Combination Tamper	Plasser - 09/32s Dynamic	23.9 Litres
Regulator	4	Broom, blades, plough	Plasser - SSP 302	11.0 Litres
Regulator (2)	5	Broom, blades, plough	Plasser - SSP 302	9.05 Litres
Regulator (3)	6	Broom, blades, plough	Plasser - SSP 302	11.0 Litres
Stabiliser	7	Ballast stabiliser	Plasser - DTS 62	9.05 Litres
Stabiliser (2)	8	Ballast stabiliser	Plasser - DTS 62	9.05 Litres

Table 2. Fuel consumption over distance travelled and track processed by resurfacing machineries.

Machine	Travel (m)	Work (m)	Q_{diesel} (L)	Practice
1	8,834	582	370	Production & re-construction
1	700	1,382	377	Production
2	19,111	3,210	313	Production & re-construction
2	9,700	830	170	Production & re-construction
3	16,624	2,814	679	Production & re-construction
3	5,300	865	370	Production & re-construction
4	8,834	502	270	Production & re-construction
4	700	790	175	Production
5	19,111	3,210	196	Production & re-construction
5	9,700	1,120	120	Production & re-construction
6	16,624	2,814	415	Production & re-construction
6	5,300	865	253	Production & re-construction
7	19,111	3,210	160	Production & re-construction
7	9,700	321	105	Production & re-construction
8	16,224	2,814	195	Production & re-construction
8	5,300	595	194	Production & re-construction

Table 3. Average results of the field data collection.

Machine and ID	Travel (m)	Work (m)	Q_{diesel} (L)	Average track processed over fuel consumed (m/L)
Tampers (1, 2, 3)	60,269	9,683	2,279	4.25
Regulators (4, 5, 6)	60,269	9,301	1,429	6.51
Stabilisers (7, 8)	50,335	6,940	654	10.61

Table 4. CO₂ emissions from railway resurfacing machineries.

Machines	Work (m)	Q_{diesel} (L)	$E_{\text{diesel-CO}_2}$ (kg CO ₂)
1, 2, 3	9,683	2,279	6088
4, 5, 6	9,301	1,429	3817
7, 8	6,940	654	1747

463

464 **Table 5.** Estimate of CO₂ emissions of railway resurfacing machines for 1000 kilometres.

465

Machine (ID)	Track processed (km)	Q_{diesel} (L)	Estimated $E_{\text{diesel-CO}_2}$ emissions (kgCO ₂)
Tampers (1, 2, 3)	1000	235,360	628,675
Regulators (4, 5, 6)	1000	155,360	414,985
Stabilisers (7, 8)	1000	94,240	251,727
Total:		484,960	1,295,387

466

467 **Table 6.** Assumptions of resurfacing machineries from previous studies.

468

Machineries	Fuel consumption per hour (l/hour)	Construction speed
Kiani et al. (2008)		
Tamping machine	15	32 hours/km
Ballast regulator	10	17 hours/km
Milford and Allwood (2010)		
Tamping machine	70	50 mins/km
Stone blowing	70	2.2 hours/km

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471 **Table 7.** Q_{diesel} comparison between Krezo et al. (2014), Kiani et al. (2008) and Milford and
472 Allwood (2010) for 1000 km of ballasted railway track resurfacing.

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Machine	Krezo et al. (2014) Q_{diesel} (L)	Kiani et al. (2008) Q_{diesel} (L)	Milford and Allwood (2010) Q_{diesel} (L)
Tamping Machine	235,360	480,000	58,380
Ballast Regulator	155,360	170,000	
Stabilisers	94,240		
Stoneblowing			159,090
Total	484,960	650,000	217,470

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477 **Table 8.** Estimated $E_{\text{diesel-CO}_2}$ emissions comparison between Krezo et al. (2014), Kiani et al.
478 (2008) and Milford and Allwood (2010) for 1000 km of ballasted railway track resurfacing.

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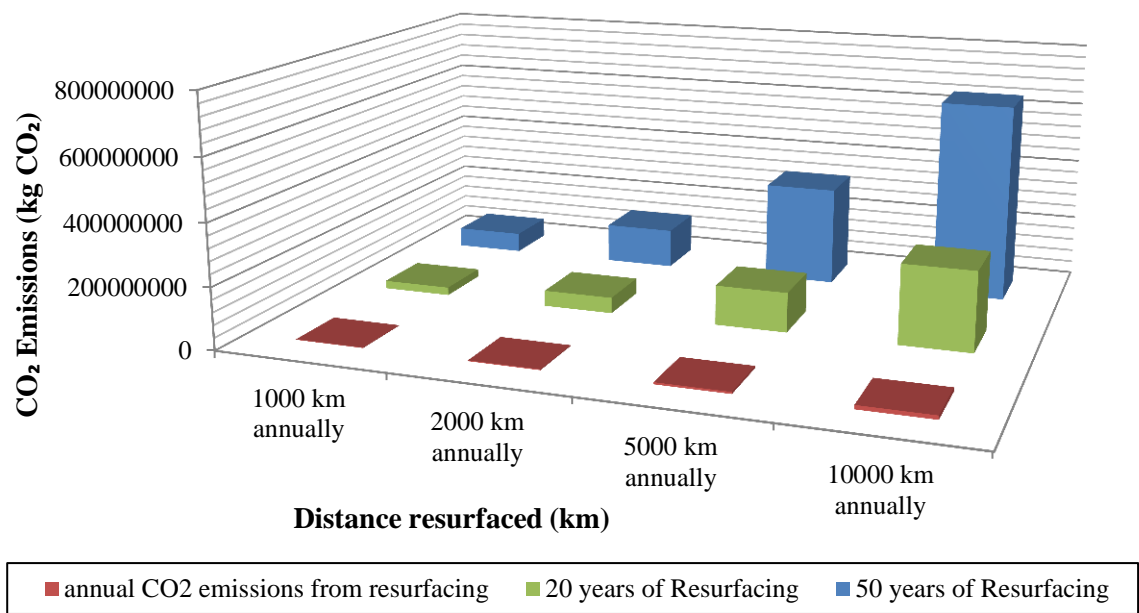
Machine	Krezo et al. (2014) $E_{\text{diesel}^{\text{CO}_2}}$ emissions (kgCO ₂)	Kiani et al. (2008) $E_{\text{diesel}^{\text{CO}_2}}$ emissions (kgCO ₂)	Milford and Allwood (2010) $E_{\text{diesel-CO}_2}$ emissions (kgCO ₂)
Tamping Machine	628,675	1,282,138	155,540
Ballast regulator	414,985	454,091	
Stabiliser	251,727		
Stone blowing			424,948
Total	1,295,387	1,736,229	580,488

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Figure 1. Projected CO₂ emissions from resurfacing activities from distances over the life of the infrastructure.